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A review of indirect evaporative cooling operating conditions and performances

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Abstract

The paper presents a review of indirect evaporative cooling (IEC) operating conditions and performances. This cooling technology is promising to develop in the near future due to its very low energy consumption and high efficiency in its range of applications. The review is presenting in details: operating conditions and performances. Having very low energy consumption comparing to classic cooling, the IEC technology is environmental friendly and has very low global warming impact. The single disadvantage of IEC is the water consumption. The review also includes a study concerning the limits of IEC for different locations world-wide.

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Keywords: Indirect evaporative cooling; regenerative cooling; dew point cooling; Maisotsenko cycle; energy efficiency

1. Introduction

The indirect evaporative cooling (IEC) technology is based on heat and mass transfer between air on one side and air with cooling water [1-3], [6-8], [11,12], [14-18], [22-26], [30-34], [36,37], [40,41].

IEC is considered a cooling technology suitable for many applications of heating, ventilation and air conditioning (HVAC) for office buildings, supermarkets, cinemas, sport centres, data centres, etc.

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The goal of this study is to present available scientific information concerning the working conditions and parameters of performance. In this study the IEC working principles are assumed as known.

2. Working conditions

The IEC working conditions were divided in: primary and secondary air working conditions; parameters of water; flow regimes; pressure drops and geometry

Available parameters of primary air, considered in the selected references are presented in Table 1 and available parameters of secondary air, considered in the selected references are presented in Table 2.

Table 1. Available parameters of primary air at inlet and outlet

Ref.	First author	Year	Geometry	Inlet				Outlet				f_p	f_{sp}[1]	w_p	Δp	Obs.
				$t_{pi,db}$ [°C]	$t_{pi,wb}$ [°C]	RH_{pi} [%]	AH_{pi} [g/kg]	$t_{po,db}$ [°C]	$t_{po,wb}$ [°C]	RH_{po} [%]	AH_{po} [g/kg]	[m^3/h]	[m^3/h]	[m/s]	[Pa]	
[2]	Alonso	1998	Vertical plates	✓	=	✓	=	✓	=	=	✓	✓	✓	N/A	N/A	R-IEC
[12]	Guo	1998	Vertical plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	IEC
[31]	Stoitchkov	1998	Vertical plates	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	IEC
[22]	Maheshwari	2001	Vertical plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	✓	IEC
[30]	Saman	2001	Horizontal plates	✓	=	=	✓	✓	N/A	N/A	✓	✓	N/A	✓	✓	IEC
[27]	Rey Martinez	2004	Vertical plates / tubes	✓	=	=	✓	✓	=	=	✓	N/A	N/A	N/A	N/A	Multiple
[10]	Elberling	2006	Horizontal plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓	N/A	N/A	M-IEC
[26]	Ren	2006	Vertical plates	✓	✓	=	=	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	IEC
[39]	Zhao	2008	Horizontal plates	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	M-IEC
[13]	Hasan	2010	Horizontal plates	✓	=	=	✓	✓	=	=	✓	✓	✓	N/A	N/A	R-IEC
[28]	Riangvilaikul	2010	Vertical plates	✓	=	=	✓	✓	=	=	✓	N/A	✓	✓	N/A	R-IEC
[29]	Riangvilaikul	2010	Vertical plates	✓	=	=	✓	✓	=	=	✓	N/A	✓	✓	N/A	R-IEC
[5]	Bruno	2011	Vertical plates	✓	N/A	N/A	N/A	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	R-IEC
[9]	Dunnavant	2011	Horizontal tubes	✓	N/A	N/A	N/A	N/A	✓	N/A	N/A	N/A	N/A	N/A	✓	IEC
[38]	Zhan	2011	Horizontal plates	✓	✓	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓	✓	N/A	M-IEC
[1]	Ahmad	2013	Horizontal plates	✓	✓	✓	=	✓	✓	✓	=	✓	✓	N/A	N/A	M-IEC
[4]	Bellemo	2013	Vertical plates	✓	=	=	✓	✓	=	=	✓	✓	N/A	N/A	N/A	R-IEC
[19]	Lee	2013	Multiple cases	✓	=	=	✓	✓	N/A	N/A	✓	✓	✓	N/A	✓	R-IEC
[20]	Lee	2013	Vertical plates	✓	=	=	✓	✓	N/A	N/A	✓	✓	✓	N/A	N/A	R-IEC
[21]	Liu	2013	Vertical plates	✓	✓	=	=	✓	N/A	N/A	N/A	N/A	N/A	✓	N/A	Multiple
[32]	Tejero-Gonzalez	2013	Vertical plates	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	N/A	IEC
[35]	Woods	2013	Vertical plates	✓	=	=	✓	✓	=	=	✓	✓	N/A	N/A	N/A	R-IEC

[1]Supply air flow rate; = Indicated values can be calculated based on other provided values

Table 2. Available parameters of secondary air at inlet and outlet

Ref.	First author	Year	Geometry	Inlet $t_{si,db}$ [°C]	$t_{si,wb}$ [°C]	RH_{si} [%]	AH_{si} [g/kg]	Outlet $t_{so,db}$ [°C]	$t_{so,wb}$ [°C]	RH_{so} [%]	AH_{so} [g/kg]	f_s [m^3/h	w_s [m/s]	Δp [Pa]	Obs.
[2]	Alonso	1998	Vertical plates	✓	=	✓	=	N/A	N/A	N/A	N/A	✓	N/A	N/A	R-IEC
[12]	Guo	1998	Vertical plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	IEC
[31]	Stoitchkov	1998	Vertical plates	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	IEC
[30]	Saman	2001	Horizontal plates	✓	=	=	✓	N/A	N/A	N/A	N/A	✓	N/A	N/A	IEC
[27]	Rey Martinez	2004	Vertical pl. and pi.	✓	✓	=	=	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Multiple
[10]	Elberling	2006	Horizontal plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	M-IEC
[26]	Ren	2006	Vertical plates	✓	=	=	✓	✓	=	=	✓	N/A	N/A	N/A	IEC
[39]	Zhao	2008	Horizontal plates	✓	=	=	✓	✓	=	N/A	N/A	N/A	N/A	N/A	M-IEC
[13]	Hasan	2010	Horizontal plates	✓	=	=	✓	✓	=	=	✓	✓	N/A	N/A	R-IEC
[28]	Riangvilaikul	2010	Vertical plates	✓	=	=	✓	N/A	N/A	N/A	N/A	✓	N/A	N/A	R-IEC
[29]	Riangvilaikul	2010	Vertical plates	✓	=	=	✓	N/A	N/A	N/A	N/A	✓	✓	N/A	R-IEC
[5]	Bruno	2011	Vertical plates	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	R-IEC
[9]	Dunnavant	2011	Horizontal tubes	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	IEC
[38]	Zhan	2011	Horizontal plates	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	N/A	M-IEC
[1]	Ahmad	2013	Horizontal plates	✓	✓	✓	=	✓	✓	✓	=	✓	N/A	N/A	M-IEC
[4]	Bellemo	2013	Vertical plates	✓	=	=	✓	✓	=	=	✓	✓	N/A	N/A	R-IEC
[19]	Lee	2013	Multiple cases	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	✓	R-IEC
[21]	Liu	2013	Vertical plates	✓	✓	=	=	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Multiple
[35]	Woods	2013	Vertical plates	✓	=	=	✓	✓	=	=	✓	✓	N/A	N/A	R-IEC

The range of working parameters of both primary (product) air and secondary (working) air are covering all climatic conditions, from cold and dry to hot and wet. The working conditions considered in experiments and simulations include both real and laboratory conditions, proving the large potential of application for the IEC technology.

Air flow rates, considered in the references are presented in Table 3.

Table 3. IEC air flow rates

Ref.	First author	Year	Geometry	Primary air flow rate [m^3/h]	Secondary air flow rate [m^3/h]	Supply air flow rate [m^3/h]	Obs.
[2]	Alonso	1998	Vertical plates	79.2	39.6	79.2	R-IEC
[22]	Maheshwari	2001	Vertical plates	4284	N/A	N/A	IEC
[30]	Saman	2001	Horizontal plates	1169.8	1169.8	N/A	IEC
[10]	Elberling	2006	Horizontal plates	2498…2565	2175…2294	N/A	M-IEC
[13]	Hasan	2010	Horizontal plates	0.00504	0.003528	0.001512	R-IEC
[28]	Riangvilaikul	2010	Vertical plates	N/A	5.14	10.44	R-IEC
[29]	Riangvilaikul	2010	Vertical plates	N/A	5.14	10.44	R-IEC
[38]	Zhan	2011	Horizontal plates	150	78	129.6	M-IEC
[1]	Ahmad	2013	Horizontal plates	1249…4147	618…1759	631…2390	M-IEC
[4]	Bellemo	2013	Vertical Plates	4200	1260	N/A	R-IEC
[19]	Lee	2013	Vertical plates	6000	1800	4200	R-IEC

Ref.	First author	Year	Geometry	Primary air flow rate [m³/h]	Secondary air flow rate [m³/h]	Supply air flow rate [m³/h]	Obs.
[20]	Lee	2013	Vertical plates	703…864	211…257	492…600	R-IEC
[32]	Tejero-Gonzalez	2013	Vertical plates	125…400	125…400	N/A	IEC
[35]	Woods	2013	Vertical plates	172.7 … 429	41.8 … 128.1	N/A	R-IEC

It is obvious that the large range of flow rates is correlated with the large range of cooling power of the different types of considered IEC equipment.

Air flow speeds, considered in the references are presented in Table 4.

Table 4. IEC air flow speed

Ref.	First author	Year	Geometry	Primary air speed [m/s]	Secondary air speed [m/s]	Obs.
[12]	Guo	1998	Vertical plates	0.5...4.5	0.25...9	IEC
[21]	Liu	2013	Vertical plates	1.6 … 6.0	N/A	Multiple
[28]	Riangvilaikul	2010	Vertical plates	1.5 … 6	N/A	R-IEC
[29]	Riangvilaikul	2010	Vertical plates	1.5 … 6	0.792	R-IEC
[30]	Saman	2001	Horizontal plates	0.7	N/A	IEC
[31]	Stoitchkov	1998	Horizontal plates	3.3	1.65	IEC
[39]	Zhao	2008	Vertical plates	0.01 … 4	N/A	M-IEC
[38]	Zhan	2011	Horizontal plates	1.77	N/A	M-IEC

It can be observed that the primary air flow speed is in the range of (0.01 ... 6.0) m/s and this parameter presented a larger interest for study, comparing to the secondary air flow speed. It is recommended a higher attention to the secondary air flow speed, because this parameter is related with the pressure loss and with the energy consumption for circulating the air through the secondary air circuit.

Air pressure drops, considered in the references are presented in Table 5.

Table 5. IEC pressure drop

Ref.	First author	Year	Geometry	Δp [Pa]	Obs.
[22]	Maheshwari	2001	Vertical plates	200	IEC
[30]	Saman	2001	Horizontal plates	200	IEC
[9]	Dunnavant	2011	Horizontal tubes	14.9 … 82.1	IEC
[19]	Lee	2013	Vertical plates	50	R-IEC

Even if the pressure drops on both air circuits are determinant for the energy consumption and for the energy efficiency of the IEC equipment, only low number of studies is considering these parameters.

Water flow and evaporation rate, considered in the references are presented in Table 6.

Table 6. Parameters of water

Ref.	First author	Year	Geometry	Water flow rate [m³/h]	Water evap. rate [m³/h]	Obs.
[30]	Saman	2001	Horizontal plates	0.288	N/A	IEC
[10]	Elberling	2006	Horizontal plates	N/A	0.001 … 0.01	M-IEC
[1]	Ahmad	2013	Horizontal plates	0.016 …0.598	0.0145 … 0.406	M-IEC
[20]	Lee	2013	Vertical plates	0.012	0.009...0.06	R-IEC
[32]	Tejero-Gonzalez	2013	Vertical plates	0.396	N/A	IEC

As it can be observed, the water flow rate and water evaporation rate are less studied, compared to the air working conditions. This is considered an important general deficit of the studies concerning the IEC, because water consumption is a key factor in the design and operation of the IEC equipment.

3. Parameters of performance

The IEC parameters of performance are: wet bulb efficiency (WBE); dew point efficiency (DPE); cooling power (CP); power consumption (PC) and coefficient of performance (COP).

Wet bulb efficiency (WBE) is defined as: WBE = ($\Delta t_{pa}/DB_{pa}-WB_{pa}$), where Δt_{pa} is the temperature variation of the primary (working) air, DB_{pa} is the dry bulb temperature of the primary (working) air and WB_{pa} is the wet bulb temperature corresponding to the inlet of primary (working) air. Dew point efficiency (DPE) is defined as: DPE = ($\Delta t_{pa}/DB_{pa}-DP_{pa}$), where Δt_{pa} is the dry bulb temperature of the primary (working) air and DP_{pa} is the dew point temperature corresponding to the inlet of primary (working) air. The cooling power (CP) is defined as the thermal power on the primary (working) air side. The power consumption (PC) is defined as the electric power consumed for producing the cooling power (CP). The coefficient of performance (COP) is defined as the ratio between the cooling power (CP) and the power consumption (PC): (COP = CP / PC).

The reported values for parameters of performances are presented in Table 7.

Table 7. Synoptic table with reported parameters of performance

Ref.	First author	Year	Geometry	WBE [%]	DPE [%]	CP [kW]	PC [kW]	COP [-]	Obs.
[2]	Alonso	1998	Vertical Plates	77 … 93	-	-	-	-	IEC
[12]	Guo	1998	Vertical plates	78 … 95	-	-	-	-	IEC
[31]	Stoitchkov	1998	Horizontal plates	79 … 88	-	-	-	-	IEC
[22]	Masheshwari	2001	Vertical plates	38…61	-	8.84 … 10.10	1.1	8.0 … 9.2	IEC
[10]	Elberling	2006	Horizontal plates	81 … 96	-	1.33	-	-	M-IEC
[39]	Zhao	2008	Vertical plates	30 … 150	20 … 100	-	-	-	M-IEC
[7]	Delfani	2010	Vertical plates	-	-	2.65 … 3.39	0.45	5.9 … 7.5	IEC
[13]	Hasan	2010	Horizontal plates	109 … 131	70 … 84	-	-	-	R-IEC
[28]	Riangvilaikul	2010	Vertical plates	30 … 155	20 … 95	-	-	-	R-IEC
[29]	Riangvilaikul	2010	Vertical plates	92 … 114	58 … 84	-	-	-	R-IEC
[5]	Bruno	2011	Vertical Plates	93 … 129	57 … 83	4.2 … 20	-	6.4 … 20	R-IEC
[9]	Dunnavant	2011	Horizontal tubes	70 … 80	-	225; (1500)*	(109.7)*	(13.67)*	IEC
[38]	Zhan	2011	Horizontal plates	10 … 140	-	0.02 … 0.43	-	-	M-IEC
[33]	Velasco Gomez	2012	Vertical plates	30 … 69	-	0.1 … 0.9	-	-	IEC
[1]	Ahmad	2013	Horizontal plates	84.2 … 95.9	58.5 … 67.4	3.8 … 12.8	0.068 … 0.746	17.2 … 55.9	M-IEC
[4]	Bellemo	2013	Vertical Plates	-	58 … 91	15.5 … 30.9	-	-	R-IEC
[19]	Lee	2013	Vertical plates	30 … 90	-	-	-	-	R-IEC
[20]	Lee	2013	Vertical plates	113 … 122	75 … 90	0.9 … 1.13	-	-	R-IEC
[32]	Tejero-Gonzalez	2013	Vertical plates	23 … 43	28 … 46	0.1 … 0.9	-	-	IEC
[35]	Woods	2013	Vertical plates	125	82 … 88	-	-	-	R-IEC

(…)* Data refers to a data centre case study where 4+1 units were used;
Each unit has IEC cooling capacity of 225 kW and direct expansion cooling capacity of 170 kW

The values of WBE higher than 100% are reported only for R-IEC and M-IEC equipment, because due to their construction, are capable of air cooling below the WB of the primary air at the inlet in the equipment.

Only a single study of M-IEC equipment is reporting the value of 100% for DPE. This study is based on simulation, but no experiment confirmed that DP can be reached in IEC equipment. The higher value of DPE reported in a study based on simulation is of 90% [20], for R-IEC equipment.

It is important no remark that the studies of IEC were mainly realised on small equipment. The CP was reported in 11 studies and in 36% of them CP < 1.13 kW. In 55% of these studies CP = (1 … 10.13) kW. In a single study the reported CP is higher than 100 kW. In this situation it is remarked a limited number of studies for commercial and industrial IEC equipment and applications, these type of equipment representing a good market opportunity.

4. Limits for the use of IEC technologies

The limits of IEC technologies in terms of cooling capacity are determined by the outside air temperature and humidity. In this study the outside air parameters were considered for the year 2013 in different locations, situated in different climate regions, according to Köppen climate classification [42]. It was considered that supply air dry bulb temperature (DS) must be constant at 22°C.

For each considered location, the daily average values were considered for: dry bulb temperature (DB), relative humidity (RH) and dew point temperature (DP).

The wet bulb temperature (WB) was calculated based on equation provided by [43]:

$$WB = DB \cdot \mathrm{atan}[0.151977 \cdot (RH\% + 8.313659)^{1/2}] + \mathrm{atan}(DB + RH\%)$$

$$- \mathrm{atan}(RH\% - 1.676331) + 0.00391838 \cdot (RH\%)^{3/2} \cdot \mathrm{atan}(0.023101 \cdot RH\%) - 4.686035$$

The arctangent function uses argument values as in radians. Values of DB are in (°C).

It was considered four possible cooling technologies:

Classic IEC equipment ("IEC");

Classic IEC equipment in dry operating regime ("DRY");

R-IEC or M-IEC equipment operating in wet regime ("R(M)-IEC");

Classic refrigeration (("REF").

The parameter of performance for the classic IEC equipment was considered the wet bulb efficiency (WBE). The parameter of performance for the regenerative R-IEC and the M-IEC equipment was considered the dew point efficiency (DPE). For both WBE and DPE were considered the values of 50% and 85%.

The “DRY” operating regime have the advantage that can provide water economy, but requires ambient temperature with at least Δt [°C], lower than the supply air dry bulb temperature (DS). In this study for Δt were considered the values of 10°C and of 7°C. In the “DRY” operating regime the outside air operate as secondary (working) air and the inside air operate as primary (product) air. The disadvantage of operating in “DRY” regime is that it requires heat transfer surface higher than in “wet” regime and the device must be dimensioned for these working conditions.

The possible operating regimes of the considered cooling technologies and their characteristics are presented in Table 8.

Table 8. Possible operating regimes of the considered cooling technologies

Code	Description	Temperatures relation	Condition
DRY	IEC in dry operating regime	DB < DS	DS – DB ≥ Δt
IEC	IEC in wet operating regime	DB > DS > WB	(DB – DS) ≤ WBE · (DB - WB)
R(M)-IEC	R-IEC or M-IEC wet	DB > WB > DS > DP	(DB – DS) ≤ DPE · (DB - DP)
REF	Classic refrigeration	DB > WB > DP > DS	-

The numbers of days/year with possible operation of the considered cooling technologies are representing the operating limits for the considered locations and are presented in Table 9.

Table 9. Number of days/year with possible operation (operating limits)

Location	Country	Climate description	Köppen code	No. of days/year							
				DRY		IEC		R(M)-IEC		REF	
				a	b	1	2	i	ii	i	ii
Athens	Greece	Subtropical Mediterranean climate	Csa	96	148	312	365	365	365	0	0
Berlin	Germany	Humid continental climate	Cfb	221	249	357	365	363	365	2	0
Bucharest	Romania	Transitional climate	Cfa/Dfa	178	211	355	363	363	365	2	0
Cairo	Egypt	Hot desert climate	BWh	12	50	226	291	291	362	74	3
London	Great Britain	Temperate oceanic climate	Cfb	214	260	363	365	365	365	0	0
Los Angeles	U.S.A.	Dry-summer subtropical	Csb	31	67	348	353	359	365	5	0
Madrid	Spain	Mediterranean climate	Csa	171	202	343	365	365	365	0	0
Paris	France	Maritime temperate climate	Cfb	208	246	358	365	365	365	0	0
Rome	Italy	Mediterranean climate	Csa	121	159	311	352	335	364	30	1
Singapore	Singapore	Tropical rainforest climate	Af	0	0	0	0	0	0	365	365
Stockholm	Sweden	Hemiboreal climate	Dfb	238	274	365	365	365	365	0	0
Washington	U.S.A.	Humid subtropical climate	Cfa	151	179	287	301	301	334	64	31

a: Δt=10°C; b: Δt=7°C; 1: WBE=50%; 2: WBE=85%; i: DPE=50%; ii: DPE=85%

It can be observed that "DRY" operating regime is the most suitable for the cold climates ("D" according to Köppen classification). This operating regime is still possible for almost all locations in the temperate climate ("C" according to Köppen classification) with the exception of Dry-summer subtropical climate (Csb), corresponding to Los Angelees (U.S.A.), where the number of possible days of operation is too low. By contrary, in the warm climates (BWh) and (Af) the "DRY" operating regime is not possible or is possible in a very low number of days.

The IEC technology can be used in all considered locations with the exception of the tropical rainforest climate (Af) corresponding to Singapore, where the high temperatures and the very high relative humidity (average over 80% in almost 70% of the total number of days).

The simple IEC technology can provide cooling capacity almost in the same measure than the more complex technologies R-IEC or M-IEC, which became more efficient as lower temperatures are required.

Since daily average values were considered for: DB, DP and RH, the number of days with possible operation have the significance that in the indicated number of days, the corresponding operating regime is possible, but not necessary for the whole day. In the case of the "REF" regime, this operation regime is required in the mentioned number of days but not necessary for the whole day.

5. Conclusions

IEC is characterised by very high energy efficiency but also by significant water consumption.

The study presents mainly practical data related with the IEC working conditions and parameters of performance.

The very different working conditions for which IEC were tested or simulated in different references proved that IEC can be used worldwide in both hot and cold climate.

The most studied parameters of performance are related to the cooling degree (wet bulb efficiency or dew point efficiency) or to the energetic performances (cooling power, power consumption or coefficient of performance).

Wet bulb efficiency (WBE) was reported between (5…155) %. Values over 100% are corresponding to R-IEC and to M-IEC, devices designed to realise the cooling as near as possible to the dew point (DP).

Dew point efficiency (DPE) was reported between (20…100) %. Highest values are corresponding to R-IEC and M-IEC devices.

Cooling power (CP) was reported between (0.1 … 225) kW. The majority of studied devices had very low cooling capacities (up to 10 kW). Only 3 devices had cooling capacities between (10…30) kW and a single device had cooling capacity over 100 kW.

Power consumption (PC) was reported between (0.068 … 1.1) kW with a special mention for a single device of 109.7 kW.

Coefficient of performance (COP) was reported between (5.9 … 55.9).

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